DOES MOTION MATTER?: COMPARING LOCOMOTION INTERFACES IN VIRTUAL ENVIRONMENTS USING PRESENCE IN DECISION-MAKING TASKS

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Abstract

As vision works at a distance, pedestrians use visual information to plan a path towards a goal. Virtual environments can replicate the visual appearance of terrain, but interfaces can confer sensations in other modalities incongruent with the visual presentation, and might therefore affect navigation decisions. I present a framework for examining the interaction of different locomotion interfaces with visual information and their effect on path choices in virtual environments, and present an experiment using this framework. For each trial in the experiment, participants moved towards a goal along one of two paths in a virtual room. The paths differed per trial in one of the following aspects: incline, friction, texture, and width. The locomotion interfaces tested consisted of a joystick and a walking-in-place metaphor. All participants were tested on both locomotion interfaces and all path presentations. Path condition, choice, time to goal, and locomotion interface were recorded per trial. Walking-in-place locomotion interfaces tended to be more natural under some visual conditions, as reflected in an increased likelihood of selecting the ecologically preferred path. Participants also exhibited a bias for traversing the right side path. I provide some observations that would improve this framework in future implementations. The novel framework provides a way of studying factors in perceptual decision making and demonstrates the effect of interface on presence and natural behaviour.

For my grandmother, the inimitable butt-kicking family matriarch, Siu-Sin (Agnes) Yung and for my scholarly curmudgeon of a grandfather, who would have loved to have read this, Sang (Simon) Lee.

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Chapter 1

Introduction

While it is well established that the quality of visual stimuli is a key factor influencing the quality of user experience in virtual environments (VEs) (Slater, Usoh, and Steed, 1995), without similar high-fidelity information from other senses such as touch, how naturally can we expect users to act in a virtual reality environment when tasked with finding a path towards a goal? In the real world, visual information is crucial to navigating and wayfinding as bodily sensory information is only available upon physical contact with the terrain (Patla, 1997). Potentially troublesome terrain conditions in the natural world can cause locomotion difficulties with examples ranging from a simple increase in energy expenditure from walking uphill (Margaria, 1968) to icy roads putting a walker at risk of injury (Gard and Lundborg, 2000). When a person visually identifies potentially troublesome terrain, we might expect that their response would be to avoid the terrain if possible.

VEs can replicate the visual appearance of terrain conditions, but we have yet to produce a locomotion interface that is capable of convincingly simulating the multimodal and complex information accessible to the bodily senses. Another major limitation is that space constraints and tracking often prevent a 1:1 mapping and consistent spatial extent between the locomotion interface and the virtual environment. Though attempts have been made to replicate the non-visual characteristics of the ground and spatial extent of an environment, these methods are often only practical for the most state-of-the-art laboratory environments (Advani, Potter, and Fernie, 2000). Even with these advanced locomotion devices, more often than not, the movements involved in using the interfaces will confer their own bodily sensations distinct from the visual presentation. It stands to reason, then, that existing locomotion interfaces, with differences in physical usage and thus different limitations, might affect navigation decisions such as the optimal path to a goal.

In this work, I propose a system for evaluating locomotion interfaces and their effect on visual decision-making in virtual environments. Questions driving this project include the following: (a) To what extent is a person's locomotor plan influenced by visual information or by the movement demanded by the locomotion interface? (b) What is the role of visual information in path planning? (c) What is the importance of economy of movement or perceived risk to a person in a virtual environment?

Chapter 2

Background and motivation

Many researchers have argued that one may measure the success of a virtual environment by how *present* a user feels when inside it. *Presence* is a subjective feeling of being (i) spatially and temporally located and (ii) having agency in an environment. There are a number of factors that influence presence, and some papers attempt to characterize them. For example, Witmer and Singer (1998) divide them into high-level cognitive factors and interface quality factors. High level factors include alertness and attention, control over the environment, and ability to block out distractions in the VE. In addition to these higher level cognitive factors, qualities of the interface also play a role; the sensory information provided and the behaviours afforded by the virtual environment ought to be as close to natural environments as possible. To place the proposed paradigm of this thesis in context, I am primarily concerned with how interface-level quality factors produce changes in higher-level decision making. Slater, Usoh, and Steed (1995) list seven variables influencing how much presence a person experiences inside a VE: (i) the ease at which a user interacts with and navigates the environment, (ii) control users have over their actions, (iii) the realism of the stimuli, (iv) familiarity with and exposure to the environment, (v) social factors, (vi) individual's cognitive differences, and (vii) how hidden the underlying system is. An ideal locomotion interface should address four of these variables: be easy to use, give a user a sense of control over their actions, provide realistic sensory feedback, and also be immersive enough that its usage does not distract from the experience of the environment (Slater, Usoh, and Steed, 1995). Familiarity with and exposure to the environment, social factors, and individual's cognitive differences are less specifically related to the locomotion interface and more to do with high-level design aspects of the environment and the personality of users.

Immersion, then, is distinct from presence, as it pertains only to the richness of the sensory information and how invisible the system implementing it is, whereas presence is a feeling of being "within" a VE. An immersive locomotion interface often allows for a user to feel a greater sense of presence (Witmer and Singer, 1998).

A common working hypothesis for those who develop VEs is that presence elicits more natural behaviours. That is, researchers in the field assume a causal relationship between feeling present and behaving realistically; the more present a user feels, the more likely they are to behave as they would in a real environment. Walking, a method of locomotion in the real environment, has yet to be convincingly reproduced virtually. Much of this limitation has to do with the fact that walking is a task involving not only vision, but multiple sensory systems – including (but not limited to) somatosensory (classically known as "touch") providing information about ground surface texture; proprioceptive (sense of one's body parts relative to one another) providing information about limb placement; and vestibular (balance and motion) senses providing information about stability, specifically the maintenance of the body's upright pose while moving or standing. If both the visual presentation and the activation of a walking interface are natural and compelling, we might expect locomotion behavior to be similarly realistic. However, as we will discuss in sections below, commonly available walking interfaces are not currently capable of such verisimilitude.

Nonetheless, attempts have been made to produce interfaces for walking in virtual environments, and with the increasing popularity of virtual reality in domains such as industry, entertainment, health and academia, it stands to reason that more will be developed in the near future. As such, a method of evaluating the effectiveness of locomotion solutions will benefit a wide number of industries and interests.

As an example, the ability to control every detail of an experiment may be appealing to those conducting behavioural research (Loomis, Blascovich, and Beall, 1999). For the current offering of assessment techniques, the success of the locomotion device may hinge more on realism and less on accuracy, speed, or other performance-based measures. Given these limitations, how much can we trust the data generated during experiments performed in virtual environments? The experimental paradigm proposed in this paper not only provides a way of measuring expectations of any given locomotion interface, but will also indicate the degree of ecological validity such an interface can offer.

As previously stated, the activation of interfaces produces their own somatosensory, proprioceptive, or vestibular cues which might not correlate with their visual presentation. Visual cues may present various path conditions, but if the physical costs are not consistent with the presented risk, then users may disregard them when planning a path inside a virtual environment. Thus, how convincing an interface is might be found by investigating the choices of the walker. If a user makes choices similar to what is expected in the real world, we may consider that interface better at facilitating presence than one for which path choices differ from the real world.

2.1 Senses and walking

Witmer and Singer (1998) describe presence as being divided into high-level cognitive factors such as alertness and attention, and interface quality factors such as the sensory information provided and the behaviours afforded by the virtual environment. To maximize the feeling of presence, the sensory information and behaviours they demand ought to be as close to natural environments as possible. Moving from one place to another naturally involves multiple sensory systems.

2.1.1 Vision

Vision offers sensory guidance and feedback to aid in locomotion. For example, *vection* is the sense of self motion that is induced through visual cues such as *optical flow* (Gibson, 1958). Optical flow can be defined as the change in visual direction of objects when they, or the self, are in motion (Gibson, 1958). The pattern made by rays of light projecting off surfaces in the environment thereby providing an observer with information from the environment is an *optic array*. (See Figure 2.1.) What an observer currently holds in their field of view will not encompass all of the optic array: species such as rabbits, with their eyes positioned on either side of the head, will see much more of the optic array than animals such as humans, with stereoscopic viewpoints that overlap, will. Thus the optic array is best described as being the potential visual field for the observer at any given point in time.

When still, a static scene appears much the same as it would in a photograph: stationary and with little distortion. When the organism moves forward, light patterns from features (such as terrain or path obstructions) in the optic array radiate outward from a point in the direction of travel with the rate of expansion proportional to the speed of forward translation. See an example in Figure 2.2. Steering (whilst looking)

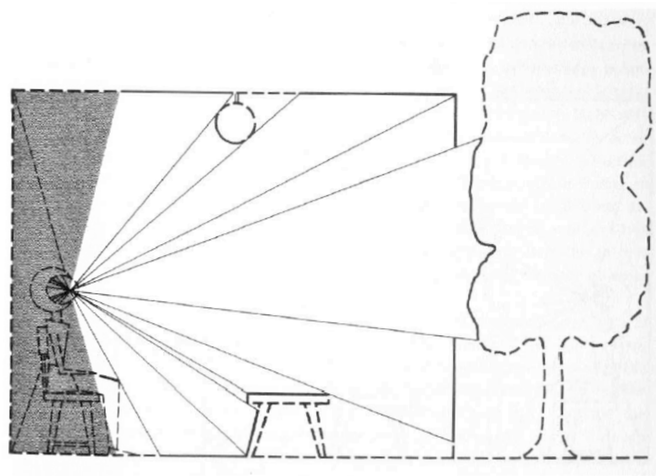

Figure 2.1: *The viewer, their optic array from a window in a room. From Gibson (1958).*

in another direction will cause the point to shift to the new location in the optic array. Researchers theorize that the mismatch between the forward feeling brought about by the movement of features on the optic array and the contradictory lack of motion signalled by the vestibular sense play a role in motion sickness in virtual environments (Hettinger, 2002; Gibson, 1958).

2.1.2 Vestibular system

The vestibular system consists of sets of organs located in the inner ears which sense angular and linear head acceleration. The organs can be subdivided into two groups: the *semicircular canals*, which sense angular head acceleration, and the *otolith organs*, which sense linear acceleration including tilt with respect to gravity as illustrated in Figure 2.3. There are three semicircular canals: the horizontal, anterior and posterior which are each aligned with one of three spatial dimensions of a head reference coordinate system. Each canal is a tube like structure filled with a fluid called *endolymph*. The canals each widen in one section (the *ampulla*,) which

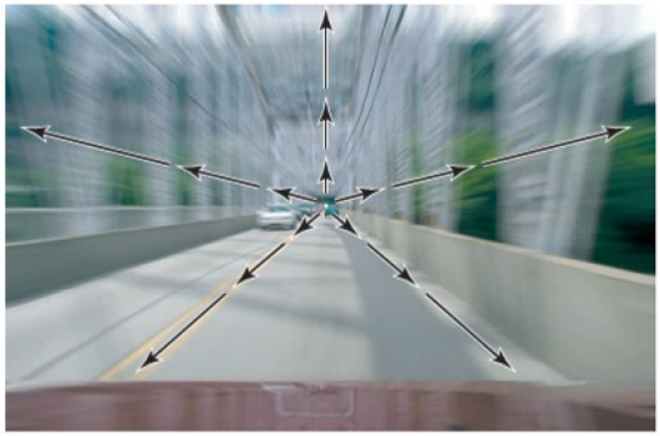

Figure 2.2: *Visual flow as it appears to a viewer moving forward. From Goldstein and Brockmole (2017).*

houses a structure called the *cupula* which has sensory hair cells embedded in its base. Angular acceleration bends the hairs in the direction opposite of acceleration, stimulating the attached nerves to fire at rates proportional to the degree that the hair bends (Goldberg and Hudspeth, 2000). *Otolith organs* consist of two structures called the *utricle* and the *saccule*. Each consists of calcium carbonate crystals (*otoconia*) embedded in gelatinous structures overlaying the sensory hair cells within the organs. Linear acceleration forces pull on the dense otoconia and thus stimulate the hair cells, allowing them to transduce the motion signals (Wolfe et al., 2006).

2.1.3 Somatosenses

Somatosenses and proprioception are, in actuality, part of the same sensory system, but are distinguished by their locality (somatosenses are located in the skin, proprioceptive senses are in the muscles and joints) and for the sake of functional descriptiveness (Rothwell, 1994). I will address the somatosenses in this section and proprioception in the following. Commonly referred to as "touch," somatosenses are a complex system

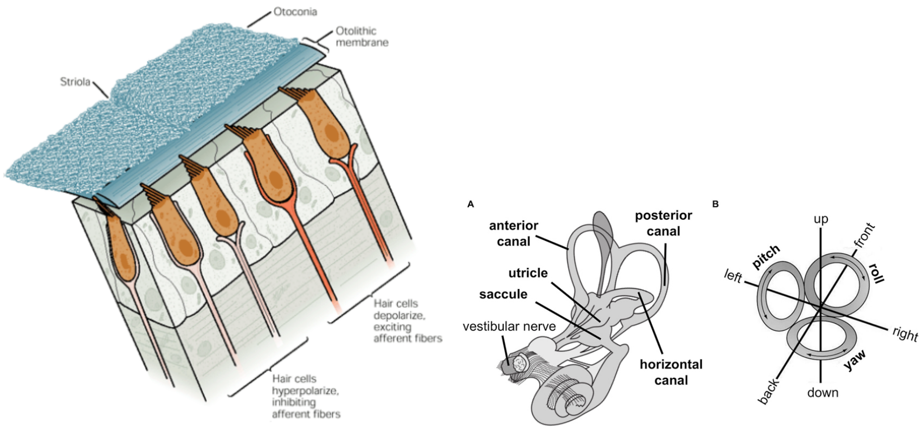

Figure 2.3: *A cross section of an otolith organ. The otoconia shift with linear acceleration and stimulate the hair cells by pulling on their ends, adapted from Goldberg and Hudspeth (2000). The semicircular canals and the direction of acceleration that they transduce, adapted from Pfeiffer, Serino, and Blanke (2014).*

of receptors located in the skin (see Figure 2.4. Though pain and temperature are also somatosenses, the senses we'll discuss in this section are the ones which respond to both minute and gross deformation of the skin surface in response to the body's movement. The information gathered from the movement of skin is often also called *haptic information* and are mostly taken in via four types of receptors located in the dermis layer of the skin. *Merkel disks* are responsible for form and texture perception, which can be useful for sensing surface properties such as irregularities and abrupt discontinuities. *Ruffini corpuscules* serve to detect the the shape and direction of body parts such as the hand or foot during locomotion by the skin stretch. *Meissner corpuscules* are activated during skin motion and function as motion detectors and aid in controlling the grip of the foot soles and toes. *Pacinian corpuscules* sense vibrations of the skin which may provide cues for a foot making contact with a surface (Foley and Matlin, 2015; Dickinson, 1974).

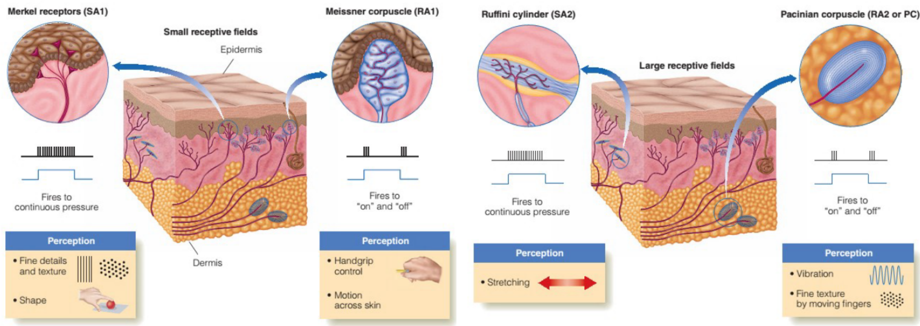

Figure 2.4: *A cross section of receptors embedded in the skin, and their respective roles in somatosensation, from Goldstein and Brockmole (2017).*

2.1.4 Proprioception

Proprioception, including kinaesthesia, is the sensation of limb position and movement. A number of receptors convey this information to the central nervous system. *Golgi tendon organs* activate when muscles exert tension on the tendons in which they are embedded. Muscles themselves host their own receptors called *muscle spindles* which sense muscle length and also, the velocity of the muscle's lengthening or contracting. Joint sensors are sensitive to joint angles (Dickinson, 1974) as illustrated in Figure 2.5. The central nervous system, sensory organs and body parts communicate using a system of afferent and efferent neural pathways. All motor plans made by the central nervous system are sent to the body parts involved in locomotion via efferent neurons. The sensory organs mentioned previously send back information, called *afferent discharge*, to central nervous system (Rothwell, 1994). Afferent signals are composed of *exafferent* and *reafferent signals*. Exafferent signals come from motion caused by other sources. (Gallistel, 1980) Reafferent signals from the muscles and joints are sent back to the central nervous system relaying the sensory consequences of the organism's own movement (Holst and Mittelstaedt, 1971). In this way, an organism knows which movements are it's own, and what sort of sensory information

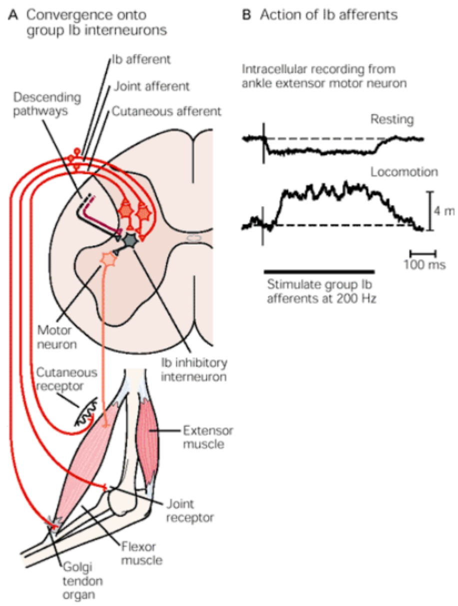

Figure 2.5: *A: Joint, muscle receptors, Golgi tendon organs and their contribution to proprioception. B: Example of nerve signals during walking and at rest. Adapted from Pearson and Gordon (2000).*

to expect as a consequence of that movement, and when something goes wrong while it is moving.

Vision, vestibular, proprioception and somatosensation play complementary roles: vision and vestibular senses offer information about the organism relative to the environment – what Gibson refers to as having "*extroceptive*" utility (Gibson, 1958); its displacement, acceleration and heading. Whereas the proprioceptive and somatosenses offer information about the body's state, such as where body parts are with respect to the body and surfaces directly contacted by the body (DiZio and Lackner, 2002). Balance strategies while walking, running and standing are classified as being either *proactive* or *reactive*. A reactive strategy for walking is employed as a response to an unexpected locomotion challenge such as an ankle adjustment to slipping on a loose tile on the ground. The senses responsible for reactive strategies are primarily somatosensory – noticing a slip on the ground; vestibular – the tilt of the head as the body moves away from the desired movement; or proprioceptive – the location of the limbs as it recovers. These senses serve to correct locomotion once proactive controls fail. Proactive balance control mechanisms involve planning and therefore vision, mentioned above as being extroceptive, is the dominant sense involved (Huxham, Goldie, and Patla, 2001).

2.2 Navigation and wayfinding

The major challenges posed to sensory systems during natural walking are firstly, that information from multiple senses relative to current and future locomotive needs or plans needs to be combined in a timely manner; secondly, the information tends to be incomplete due to the very nature and limitations of our senses; and thirdly, information received by senses, even within a single sensory system is partial and can therefore be ambiguous or even contradictory in cases where multiple modalities are operating on the same task (Howard, 1997). The prevailing theory is that a person holds a cognitive model of their bodies and the surrounding environment. This model is continuously modified by sensory input, and by either conscious or unconscious and/or innate processes. (Whitton and Razzaque, 2008). An example Gregory (1970) commonly used by researchers and educators of how hypotheses are modified is that of a person in a train watching the windows on either side of them. On the window to the left, a train starts moving and causes a feeling of vection, an innate perceptual phenomenon. To the right, the features of the scenery stay stationary, which conflicts with the illusory movement. The mix of moving and stationary scenery causes temporary disorientation until the person realizes that they are indeed stationary. The model is then updated to reflect the fact that the train on the left is moving, while their train is staying still. For this reason, interfaces with large displays, all else being equal, tend to be more effective in inducing illusory motion in users as they block out more of the real world and thus, conflicting sensory information.

Information received by the senses is used to inform strategies for moving towards a goal, whether the goal is beyond the bounds of an organism's perception or an intermediate one on the way to an ultimate end point. Unlike colloquial uses of the term *navigation*, we will use it to refer to the aggregate of cognitive and motoric aspects of directed, goal-oriented self motion (Chrastil and Warren, 2012). *Wayfinding* refers to the cognitive element, and locomotion, the motor activity. Locomotion is the act of purposely moving oneself from one place to another (Whitton and Razzaque, 2008). A cognitive model for high-level navigation was proposed by Jul and Furnas (1997) and further developed by Darken and Peterson (2002) wherein the bodily senses and vision interact at the perception-assessment-motion loop. At times, spatial knowledge is retrieved through secondary sources, conveyed through representational means such as by maps or by instructions provided to us by others. Most of the time, however, we obtain spatial knowledge directly from the environment itself.

For terrestrial beings such as humans, the environment has a consistent point of reference to which the organism must maintain contact: the ground. Down is given form in the downward acceleration of gravity, exerting pressure on the limbs, the feel of the floor underfoot, the visual horizon, as well as other visual cues (Gibson, 1958). The act of moving involves pushing off against the ground and therefore maintaining or increasing the stability of footing is important. *Paths* are surfaces extending from the animal's current location that are also traversible using its form of locomotion; whereas the term *barriers* denote surfaces which prevent locomotion. Paths and barriers have transitional gray areas between them, surfaces which allow movement, but nonetheless impede the walker, or at the very least, are not ideal walking surfaces in some way. Therefore, the ground surface, while effectively continuous, can change characteristics as an organism walks, and these changes, such as its solidity, are often associated with visual change in texture or pattern. Depending on the locomotion abilities of the organism, a given terrain can provide different walking possibilities or lack thereof. Previous experience is often how an animal understands which surfaces are more desirable than the rest (Gibson, 1958).

2.3 Locomotion interfaces and examples

The position of the user in the virtual world is often expressed as point in three dimensional virtual space. The position (in x,y,z coordinates) and orientation (yaw, pitch, roll) of their body and head determines their relationship to the environment including their view point. A locomotion interface serves as a method of translating a command from the user into a change in their position and/or orientation. Upon detecting an intent to move, the locomotion controller, be it using buttons, mice, switches, or a motion tracking system – produces a displacement vector to modify position. This change in position then causes an update of the display to simulate locomotion in the appropriate direction and at the appropriate speed. Locomotion methods in a VE tend to fall into three categories: piloting, simulated walking, or magical. An interface that shares similarities to vehicles like cockpits or dashboards are piloting interfaces. These tend to be used in more specific situations, such as in industry or aerospace training, and thus, are not directly relevant to this thesis (Whitton and Razzaque, 2008). When scenes are sufficiently large, some virtual environments make use of "magical" locomotion methods to augment walking methods by analogies such as teleportation or portals. Scene grabbing interfaces (wherein a user selects a point in the environment using a pointing device and drags their viewport towards the point) may also count as a subtype of magical interfaces (Mine, Brooks Jr, and Sequin, 1997). While the design and evaluation of these methods pose interesting questions, they lack realism. The focus of this thesis will be on simulated walking.

Simulated walking techniques are meant to imitate more natural human motion and can be classified into four classes with some overlap: 2-dimensional "flying" interfaces, treadmills, real-world walking, and walking-in-place interfaces. Two-dimensional flying interfaces in VEs provide a user with control over the viewpoint via two-dimensional left/right and forward/back movements. The feeling is akin to being placed on a flatbed truck or magic carpet that one can steer around (Robinett and Holloway, 1992). A joystick device is often used as a flying device as it allows for two dimensional control of movement with control of speed. Using the arrow buttons on a standard keyboard may also serve as a flying interface (Whitton and Razzaque, 2008). Treadmills can be passive, such as the Sarcos Treadport (Christensen et al., 2000), requiring physical effort on the part of the user and moving passively to counter the user motion; or they can be motorized: sensing the user's position and changing speed to keep the person squarely in the centre of the belt, such as the Cyberwalk 3D (Souman et al., 2011). Real-world walking, often implemented with either body sensors or motion tracking, utilizes the entirety of a space and may make use of techniques such as redirected walking, which exploits human tolerance for small misalignments between visual and proprioceptive scene perception in order to adjust a user's heading unbeknownst to them, and thus accommodate for the physical limitations of the area (Steinicke et al., 2009).

Walking-in-place (WIP) interfaces take in the position of body parts as input to the system. The user makes walking, stepping, or even arm-swinging motions but physically remains in the same place. A stepping method described by Yan, Allison, and Rushton (2004), the Gaiter system by Templeman, Denbrook, and Sibert (1999) and an arm-swing speed system by McCullough et al. (2015) are examples.

2.4 Previous work

Schubert, Friedmann, and Regenbrecht (2001) demonstrated that naturalness of interaction is a major component of presence. Coined "interface awareness" and "realness," interfaces which are sufficiently unnatural can result in reduced presence. Previously, I mentioned that large displays are better at hiding conflicting sensory information by virtue of occluding a user's view of the real world. Locomotion interfaces should be no different in that providing consistent, immersive, and high fidelity sensory information should enable greater presence. Movement within the space of a VE using unnatural interfaces require additional attentional resources which could otherwise go towards the user's overall experience of a VE. Therefore the implementation of an interface that elicits natural behaviour is desired for many applications – such as for psychological, therapeutic, and clinical purposes. I propose that naturalness of locomotor behaviour can be treated as an objective correlate of presence in so far as interface design is concerned. As such, various means have been proposed as a way of measuring how much presence an interface provides. These include questionnaires, physical measures, and task performance studies.

The easiest and least intrusive way is to use rating scales and questionnaires: a straightforward approach considering that presence is defined as a subjective feeling. Much of the groundwork for this was laid in the mid nineties by two studies: a sixty-one question metric categorized into three subscales by Witmer and Singer (1998), and a questionnaire of six questions by Slater, Steed, et al. (1998). Unfortunately, the design of a questionnaire or the way a question is posed requires great care to avoid any potential ambiguity of terms or of expectations. As an example, the terms "realism" and "immersion" are often conflated. *Realism* refers to the verisimilitude of the stimuli, and *immersion* the completeness of sensory experience inside the VE and exclusion of sensory information from outside the VE. Thus if the experimenter and subject have different concepts in their mind, the reliabilty of the questionnaire or testimony could be suspect. Moreover, the rating scale might be internally consistent, but not externally meaningful. To illustrate this point, Usoh et al. (2000) found that the two questionnaires introduced by Witmer and Slater did not produce presence scores reliably higher for walking in real life compared to in virtual environments.

If objectivity is desired, then designers of interfaces cannot simply rely on user testimony or rating systems. Though feelings are subjective and private to an individual, internal states often also produce observable effects (Deniaud et al., 2015). An objective method which would avoid some pitfalls of questionnaires or testimonies, is to use physiological measures such as heart rate and skin conductance to infer the amount of presence. Increases in skin conductance or the heart rate from a particularly stressful or engaging scene may indicate greater presence (Nacke and Lindley, 2008). Higher frame rate and lower latency reportedly increased users' heart rate during VR simulations of stressful situations such as falling from a dangerous height (Meehan et al., 2005). Major downsides to these approaches are their intrusive natures, reliance on extreme scenarios, and often complicated machinery needed to use them. In addition, studies such as that by B. K. Wiederhold, Davis, and M. D. Wiederhold (1998) noted that physiological measures are often only useful in stressful or extreme situations, and failed to show a systematic relationships between presence and physiological metrics.

Some studies investigating locomotion interfaces have thus emphasized a user's task performance on different locomotion interfaces. The measure of performance may use a number of variables such as speed and accuracy in reaching a walking target. For example, Ruddle, Volkova, and Bülthoff (2013) tracked collisions with obstacles in the environment and Sargunam et al. (2017) used head rotation accuracy. Other studies take a more high-level task approach such as that by Grant and Magee (1998) who had participants navigate a virtual museum to find certain landmarks and then compared their speed and accuracy to those who learned the museum's layout with a map and those who learned by walking in real life. While performance studies share some similarity to the experiment presented in this thesis, there are some differences. Task performance experiments have a few drawbacks. Firstly, the the process of calculating and data gathering for task performance may be complex. For example, navigating the spaces in the Grant and Magee (1998) and Ruddle, Volkova, and Bülthoff (2013) papers requires tracing the exact the route taken by the user's walk through the VE, whereas the method in this thesis merely requires keeping tally of participant choices at each trial. Another possible issue arising from task performance studies is that the results may not be broadly generalizable. Football maneuvers seen in Williamson, Wingrave, and LaViola (2010) are hardly generalizable to all real life locomotion settings or ordinary people untrained in the movements. Also, tasks used in the study may not be contingent on presence.

The approach I am proposing was to an extent inspired by similar studies of biological pathfinding in animals such as anoles and ratsnakes (Jones and Jayne, 2012; Mansfield and Jayne, 2010), and shares some similarity to the study by Grant and Magee. Animal studies are helpful insofar as they can provide starting points for the purpose of creating a testing framework which offers simple and intuitive results. The animals are given a number of different routes to choose from with different properties. Alternatives that make it easier for the animals to stabilize and move are generally chosen more frequently than not. As an example, anoles preferred perches with wider diameters and thus more surface area so that their toes could more easily grip them and launch them to the next platform (Jones and Jayne, 2012). Snakes, having no limbs and moving only with belly scales, preferred surfaces with fewer gaps between them and preferred straight passages as opposed to those with a 90-degree turn (Mansfield and Jayne, 2010).

Following the logic of these animal studies, in this paper we consider a comparison method for assessing the success of an interface. As a measure we use the conformance of behavioral choices with expectations of natural real world behavior. We test the hypothesis that the interface which produces natural behaviour more frequently or reliably is therefore more realistic to the user. We assess this by comparing choice responses with a less natural “traditional” gaming interface with a more immersive, naturalistic VR locomotion technique. As these interfaces contrast widely in their sensory involvement, the choice responses will likely differ greatly. Traditional video game controllers such as gamepads and joysticks, are ubiquitous interfaces. These devices are overwhelmingly the interfaces of choice in most settings, and despite how little they resemble true walking, if the popularity of video gaming is any indication, those who play games appear capable of experiencing immersion and presence using these devices. Still, we expect that such interfaces will not elicit the same degree of presence as a more natural interface. This comparison method is, unlike studies utilizing specialized task performance metrics, easily done by most subjects with typical mobility and vision. As naturalness of interaction is a major factor in inducing presence, this method should provide more objectivity than questionnaires, whilst being more reliable than physiological measures. It is also unobtrusive and therefore unlikely to be distressing or confusing to users. This thesis, then, rests on the conjecture that naturalness of movement whilst using a locomotion interface results in increased presence which in turn is reflected in increased naturalistic behaviour.

Chapter 3

Methods

To understand how visual path information and locomotion interfaces influence decision making in virtual worlds, I built a series of virtual rooms, each with two pathways leading to two goal choices. The experiment was designed, rendered and conducted using Vizard 5, a Python/OpenGL-based toolkit (WorldViz LLC, 2015). Some of the models were made using a combination of 3ds Max® (Autodesk, 2015) and Blender (Blender Online Community, 2015).

The images were displayed on a eight-projector quasi-spherical curved screen referred to as the "Wide-Field Immersive Stereoscopic Environment" (WISE) that fills a user's visual field. The user was positioned inside a indentation in the bottom middle of the system, centering their head in the display. The environment was rendered by a computer cluster consisting of a single master node and 8 client nodes running hardware synchronized Nvidia Quadro 4000 graphics cards. We chose to use a projected display, as most available head-mounted displays have (at the time of writing) comparatively limited resolution (for comparison: 8 projectors at 1920×1200 each versus 1080×1200 for the Oculus Rift and HTC Vive (*Oculus*

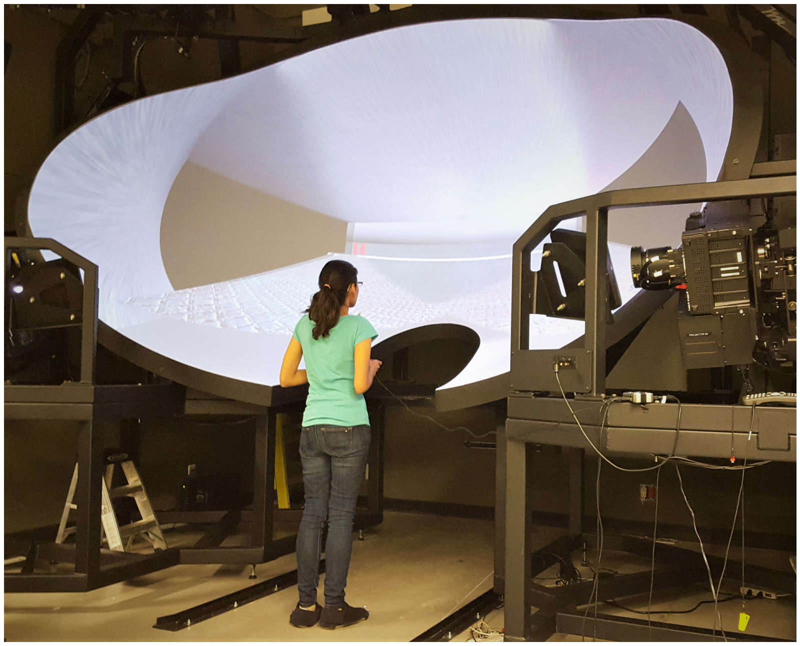

Figure 3.1: *A participant using the joystick interface. In the actual experiment the room lights were extinguished and only the display was visible.*

Device Specification; *VIVE Specs & User Guide - VIVE Developer Resources*)) and will obscure a participant's real body, preventing them from knowing where their body parts are in the real environment increasing the likelihood of colliding with real world objects or losing balance (Darken and Peterson, 2002).

All participants used both interfaces in separate blocks of trials. For each trial, participants moved their avatar from a starting position towards one of the two goals in the virtual room requiring them to make a choice between two paths to complete the trial. Each path consisted of a plank raised above the ground, equivalent to about 40 meters in length. The goals were marked by red doors which opened when the participant was in close proximity. The room would reset itself when the participant moved through the door, whereupon the participant was moved back to the starting position and a new condition was randomly presented. If a participant were to step off the offered paths, they were transported back to the starting position and the misstep recorded. The participants were told to make their decision and walk as quickly as possible, as the walkways disappeared at random with an increasing likelihood proportional to the amount of time elapsed in the trial. Falling as a result of plank disappearances were included in the total fall count. This timer reset after being tripped and at the start of a trial.

The two path choices differed in one aspect per trial. These aspects were: (a) slope: level or going upward, (b) specularity: shiny or matte, (c) textured: rubber, stone, gravel, (d) width: wide, medium and narrow. Each pair of comparisons within each aspect was tested twice, with the path conditions flipped between left and right paths. For example, both left: shiny, right: matte and left: matte, right: shiny were tested for each locomotion interface and each user. See Table 3.1 for the complete list of conditions. Locomotion interfaces used were joystick control and a walking-in-place metaphor, both described in following sections. Both interfaces were tested in separate blocks – that is, one block for each of the two interfaces with each block consisting of 16 trials, totalling (16×2) 32 trials. The order of trials within a block was computer-randomized and block order was counterbalanced to control for ordering effects. Path condition, choice, time to goal, locomotion interface and missteps were recorded as data. Missteps are defined as stepping off the either the planks or any of the raised areas of the environment onto the ground, which was given a lava texture as a visual deterrent.

To assess the possible biases stemming from individual aptitudes and preferences, participants were given a modified multiple intelligences inventory containing a subset of the questions (shown in Table 3.2) measuring only kinesthetic and visual-spatial scores (Brady et al., 2012; Tirri and Nokelainen, 2011). The results of the inventory were used as a covariate. For most participants, given the ubiquity of video

Joystick	Walking-in-place metaphor
L: narrow, R: moderate	L: narrow, R: moderate
L: moderate, R: narrow	L: moderate, R: narrow
L: wide, R: moderate	L: wide, R: moderate
L: moderate, R: wide	L: moderate, R: wide
L: narrow, R: wide	L: narrow, R: wide
L: wide, R: moderate	L: wide, R: moderate
L: up, R: level	L: up, R: level
L: level, R: up	L: level, R: up
L: shiny, R: matte	L: shiny, R: matte
R: shiny, L: matte	R: shiny, L: matte
L: rubber, R: stone	L: rubber, R: stone
L: stone, R: rubber	L: stone, R: rubber
L: rubber, R: gravel	L: rubber, R: gravel
L: gravel, R: rubber	L: gravel, R: rubber
L: stone, R: gravel	L: stone, R: gravel
L: gravel, R: stone	L: gravel, R: stone

Table 3.1: *All visual path conditions*

gaming, their primary experience in virtual environments will be in the form of video games, therefore we must assume that at least some have a degree of familiarity moving around with video gaming interfaces. Presumably, as joysticks are a mature technology: unobtrusive, inexpensive and readily available in conventional gaming markets in comparison to newer, exotic interfaces made with virtual reality in mind, it stands to reason that most participants who play video games will be more familiar with joysticks and gamepads than with non-traditional gaming interfaces such as walking-in-place. Participants were therefore asked questions about gaming habits as seen in Table 3.3; specifically whether they regularly and/or recently played games, and what sort of games they played. For the purpose of this study, participants who answered at least somewhat often on either questions 2, 3 or 4 were classified as "gamers." To clarify, we defined "often" as being on a weekly to semi weekly basis, and specified only for games presented in a 3-dimensional perspective.

In total, there were 26 participants (15 male, 11 female) ranging in age from 19 to 59 years (M = 29, SD = 10.4, median = 27) recruited by word of mouth and from the York University community. Additional data was obtained from six participants,

1. At school, geometry and various kinds of assignments involving spatial perception were easier for me than solving equations.
2. I have a talent to form a mental picture of objects by touching them.
3. I am very good at tasks that require good coordination.
4. When I think, I can see clear visual images in my mind.
5. I am able to see objects or events that I would like to document on camera or video.
6. I usually find my way, even in unfamiliar places.
7. I am handy.
8. I can easily do something concrete with my hands (e.g. knitting and woodwork)
9. I am good at jigsaw puzzles, picture puzzles and various kinds of labyrinth puzzles.
10. I am good at showing how to do something in practise.
11. It is easy for me to imitate other peoples' gestures, facial expressions and ways of moving.
12. I often "talk with my hands" and/or otherwise use body language when talking to someone.
13. I can easily imagine how a landscape looks from a bird's-eye view.
14. I'm good at drawing and designing various kinds of figures.
15. When I read, I form illustrative pictures or designs in my mind.
16. I was good at handicrafts at school.

Table 3.2: *Learning styles inventory, on a 5-point scale*

1. Do you play video games (yes/no)
2. How often do you play isometric/top-down viewpoint games?
3. How often do you play first person viewpoint games?
4. How often do you play quasi-first person view point games (i.e. over the shoulder shooters)?
5. How often do you play games that are not represented in the above three categories

Table 3.3: *Video gaming questionnaire, on a 5-point scale*

1. It was easy to control my direction of motion.
2. When I started moving, it felt like I was immediately moving forward in the VE.
3. When I stopped moving, it felt like my motion in the VE stopped appropriately.
4. My speed in the VE was consistent with how fast I would expect to move.
5. Overall: walking in the VE is natural.

Table 3.4: *Post-experiment interface evaluation questionnaire, ranked on a 5-point scale*

but the data was invalidated due to technical issues with the display arising during the experiment. Sample size was chosen on the basis that this study is meant to be an exploratory study of the utility of the navigation decision paradigm, and similar studies used 20-30 participants (Usoh et al., 2000; Nacke and Lindley, 2008; Deniaud et al., 2015; Heydarian et al., 2015). Participants were briefed on all requisite safety procedures and their rights prior to the experiment, asked to fill in the multiple intelligences inventory described above in Table 3.2 and answer the video gaming questionnaire in Table 3.3. A coin was flipped to decide which of the interfaces they would use first – heads: joystick, tails: walking-in-place.

In the experiment, the participants were instructed to walk from the starting area across the planks towards either door. They were informed that there was a chance that the planks would disappear and drop them into the "lava" below and that the likelihood would increase the longer the trial took. The trial would then reset, requiring that they start the trial over. This means that they were to get across as quickly as they could, but also to be mindful not to steer themselves off the platforms. A practice trial featuring a flat, neutral surface and no lava, was provided at the beginning of each block so that participants could familiarize themselves with the walking interfaces.

Between interfaces, participants answered the five questions about their experience with each interface implementation shown in Table 3.4. Details on the conditions, both visual path conditions and locomotion interface conditions are in the following section.

The results of the experiment were analyzed using the Matlab (MATLAB, 2015) computing environment, Statistics and Machine Learning Toolbox package.

3.1 Path conditions

Conditions are (a) inclined: 20 degrees upward and level (b) specularity: shiny or matte, (c) textured: rubber, stone, gravel, (d) width: wide, medium and narrow. These conditions were chosen primarily based on their ease of implementation in the VE and are not intended to be exhaustive or considered factors in and of themselves. Future implementations of this paradigm may utilize more or less of these conditions, or perhaps even employ combinations of them. For this thesis, we compared choices between paths differing along only one visual dimension at a time. As per the animal studies discussed previously (Jones and Jayne, 2012; Mansfield and Jayne, 2010), what we considered the natural choices were the ones that presumably resulted in lower metabolic costs and minimized risk of falls and/or postural instability.

3.1.1 Slope condition

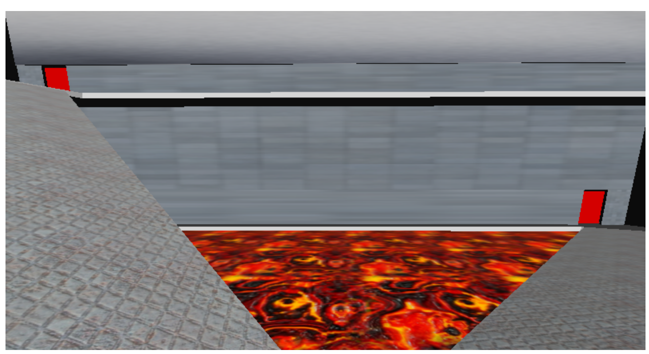

Figure 3.2: *Example of an incline condition trial*

There are two phases to stepping on a level surface: a positive work phase, which roughly correlates to the lift and acceleration of the body's centre of mass and that is counterbalanced by an equal in magnitude negative work phase in which the body's centre of mass is moving down and decelerating. In the real world, walking at different slopes makes different demands on the body during different step phases (Minetti, Ardigò, and Saibene, 1993). Generally speaking, walking uphill, the work in the negative phase decreases with the inclined ground while the positive increases to make up for the increased vertical distance. Walking downhill results in the opposite; the work in the negative phase increases as more energy is required to decelerate, but the work in the positive phase decreases with the pull of gravity. Though initially, at gentle slopes, it seems that the two work phases cancel each other out, the trade off between positive and negative work during inclined walking in general is unequal in magnitude. Eventually uphill walking at a slope greater than 22% results in little to no negative work, while the positive work increases progressively. Walking downhill at a slope results in no positive work, while the negative work continues to climb (Margaria, 1968). Thus, after the thresholds of 22% and -9%, the metabolic costs of walking sloped paths go up, and we expected that walkers will favour paths that do not slope. With this in mind, for the incline condition, the path was inclined either 20 degrees upwards from the starting position, roughly correlating to a 25% incline or level (a 0% incline). It was expected that most users would prefer the level path, as walking uphill in the real world increases energy expenditure (Margaria, 1968). At this time, we did not test downhill slopes. For trials where the incline condition was not being tested, both paths were level. Paths were the same length, whether inclined or not. Shown in the figure above is an example of one of these trials (Figure 3.2).

3.1.2 Friction condition

Stepping on a low-friction surface is inherently risky for tall bipeds with high centers of gravity such as humans. During a step in bipedal walking, the sole of one foot, the "stance" foot, supports the centre of mass while the other, the "swing" leg lifts off the

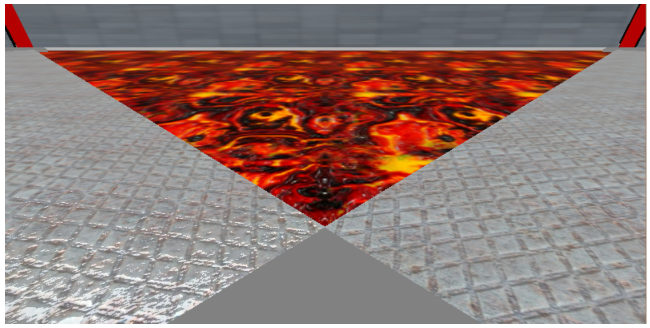

Figure 3.3: *Example of a friction condition trial*

ground (Huxham, Goldie, and Patla, 2001). The step completes when the centre of mass is again evenly distributed between the two feet. Low-friction surfaces increase the likelihood that either of the feet could slide from failing to adequately grip the walking surface, thus increasing the risk of falls. To add to the danger, bipeds, having only two legs for trunk support, cannot shift their weight to other legs if their stance foot loses balance (Li et al., 2010). Higher specularity conveys an amount of friction to be expected on the walking surface (Fleming, 2014), similar to the appearance of ice or water on the ground. Those familiar with cold or wet environments are likely aware of the hazards posed by walking on low friction surfaces. Strategies for minimizing the risk usually involve maintaining the centre of mass lower during locomotion, reducing step velocity and shortening the length of a step (Li et al., 2010). These accommodations decrease the metabolic efficiency of walking. For this testing condition, a path was either shiny, with a specularity of roughly 30% or matte, with no specularity. Where the friction condition was not tested, the default texture was matte. The image above provides an example of one of these trials (Figure 3.3).

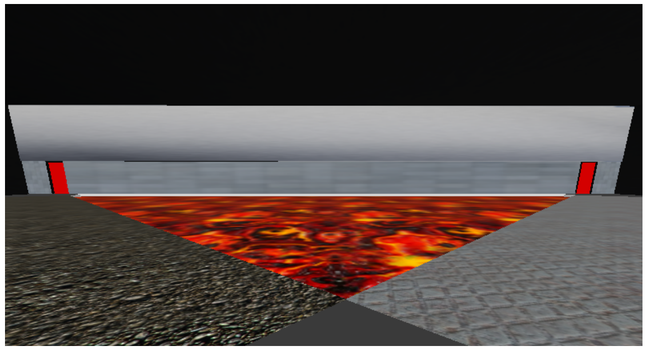

Figure 3.4: *Example of a texture condition trial*

3.1.3 Texture condition

Ground texture provides information about how stable and compliant the walking surface is. A foot stepping on surfaces such as gravel on the ground sinks and the material can also shift underneath the weight of a walker (Gates et al., 2012). During the swing phase, having a foot planted on shifting and uneven ground means more muscle activation in the muscles surrounding the knee and ankle joints for stabilizing the body, and consequently, increased energy expenditure. The knee and hips bend farther in pushing off the ground when initiating a stride to compensate for the ground compliance and also, if the ground variability is indeed high enough, to maintain adequate toe-to-ground clearance as the foot leaves the surface for avoiding trips. Additionally, the variance in the terrain itself forces variable timing in the steps themselves, which unbalances the energy exchanged between the positive work phase and negative work phase of stepping (Voloshina et al., 2013). For a compliant, unstable surface, we selected a gravel texture. A stone surface is uneven, but is not unstable. The default rubber ground texture was also used. Other implications are possible with texture conditions, but I purposefully limited the analysis to stability/compliance/uniformity for the time being. Figure 3.4 shows an example of the texture condition with gravel and rubber. It is expected that the gravel condition will be the least favoured, stone to be favoured more than gravel, and rubber favoured above the others.

3.1.4 Width condition

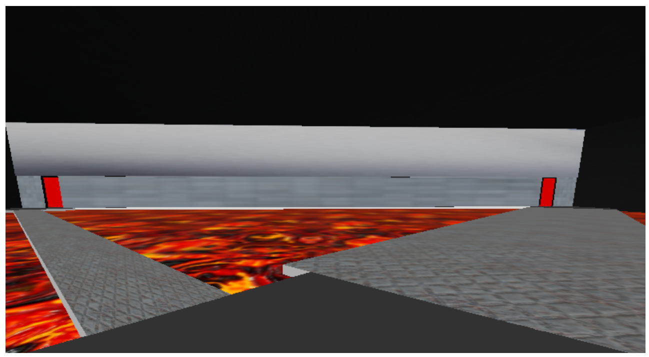

Figure 3.5: *Example of a width condition trial*

Bipedal motion produces unavoidable lateral (side-to-side) instability when redirecting the centre of mass laterally from the standing leg onto the swing leg. Thus, during normal unconstrained walking, people will step with their feet placed roughly 12% of a leg length apart, which provides the best compromise between efficient walking and lateral stability (J. Donelan et al., 2004). The trade-off with a narrower step width, is that the stepping leg needs to move laterally to avoid colliding with the standing leg while counterbalancing and maintaining the center of mass within the bounds of the base of support lest they fall off the path (J. M. Donelan, Kram, and Kuo, 2001). For this experiment, paths were either wide, moderate or narrow (about 8, 6 and 2 feet, respectively.) At a narrow enough width, participants were expected to spend more effort consciously trying to maintain equilibrium on the path. Therefore the narrow width path was expected to be favoured the least, with mid-width paths favoured more than narrow. As we did not otherwise restrict the foot placement in the wide path condition, the wide path was predicted to be favoured at least as much as the mid-width path, if not more, due to the larger margin of error for a participant's foot placement. Due to limitations of the system and my focus on visual decision making, we could not actually model the lack of equilibrium in narrow conditions. The example image is of narrow and wide path choices (Figure 3.5).

3.2 Locomotion interfaces

The locomotion interfaces tested were joystick control and walking-in-place metaphors. Other locomotion interfaces such as linear and omnidirectional treadmills were considered, as treadmills would provide greater proprioceptive similarity to walking compared to our WIP method, but were dropped to limit the scope and complexity of the study. WIP and joystick interfaces contrast greatly in their usage and sensory similarity to natural walking. Details on their characteristics are described in the sections below.

3.2.1 Joystick

Joystick control, as mentioned above, is sometimes called "joystick flying" in the literature due to its similarity to how one would feel as if standing on a flying carpet (Whitton and Razzaque, 2008). This locomotion type best represents what is currently the most ubiquitous locomotion control in home entertainment, but offers little to no realistic somatosensory, proprioceptive or vestibular feedback. We expected this locomotion interface to perform poorly relative to the other in terms of naturalness of locomotor decisions.

The joystick used for this experiment was a Logitech dual analog joystick, meaning that two small joysticks are controlled with either thumb. Pushing the left joystick forward provides a variable-speed forward translation. Variable-speed orientation (pitch and roll), including left-right steering is controlled using the right joystick.

3.2.2 Walking-in-place

Walking-in-place metaphors offer greater proprioceptive and somatosensory similarity to natural walking than joystick control. However, in this implementation, the user simply steps in place: there is no full body translation during striding and therefore less vestibular feedback.

Figure 3.6: *Sensors placed on the feet*

The WIP metaphor was an implementation of the stepping-in-place approach described in a paper by Yan, Allison, and Rushton (2004). Forward translation speed was determined by the user's foot speed – the faster the feet moved, the quicker the user traveled in the VE. Trackers were placed on the toes of shoe covers which were then fitted over the participant's feet and were tracked in six degrees of freedom using an OptiTrack V120:Trio infrared motion sensor array set in front of the feet. (See figure 3.6 for an image of the marker placement.) When movement speed exceeds a threshold for either foot, the algorithm identifies which foot is in stance, which foot is lifting, and models the user's gait to approximate the walking speed. The user's viewpoint is updated when the lift leg is judged to be either initializing, midway through, or terminating its movement. The speed of forward translation is estimated using a Kalman filter from the speed of the swing leg lift, smoothed over with a five point differentiator. A Kalman filter uses a measured speed and previous estimations to calculate a new measurement which optimally accounts for the error between measurement and previous estimation, thereby converging on the actual value. In this way, as foot speed was measured from initializing to terminating lift, the viewpoint moves forward at a reasonably accurate rate.

In a divergence from the original implementation, instead of using the rotation of the torso (via trackers placed on the hips) to change direction, the direction of translation was determined by the angle of rotation of the user's head. This is accomplished by using Vizard's head-trackers located on either side of 3D shutter glasses. For this experiment, we only used the glasses for tracking and did not present stereo images. The infrared sensors for head tracking were located on the top of the screen assembly.

Chapter 4

Results and Analysis

To restate the hypothesis, the responses are expected to be natural more often in the walking-in-place interface condition than in the joystick condition, across all visual conditions. For the dependent variable, we compared the participants' responses to the expected responses to each trial based on putative energy expenditure as detailed above in Chapter 3.1. We predicted that participants would choose paths exhibiting conditions that in the real world, would minimize energy expenditure more often using the WIP metaphor when compared to using the joystick. For each participant on each trial we recorded whether the response matched the metabolically preferred response or not.

Because the users either chose the expected response for each condition or not, the response data is binomial in its distribution, which poses a problem for most linear regression analysis because the resulting residuals (the differences between predicted and actual values) cannot be normally distributed. This motivated our use of generalized linear mixed model analysis using a logit link function to model the likelihood of choosing the expected path as a function of the independent variables. The response is a natural log of the probability that y is either "expected" or "unexpected," that is, for k predictors: $Ln(P/1-P) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k$, where β are weights, P is one of the outcomes, and X are predictor variables.

The experiment was a repeated-measures design: participants saw each combination of path choice twice, with the right/left path conditions flipped across presentations. Also, a subject term was necessary to account for individual differences, given the highly personal nature of experience and presence. This term accounts for the repeated measurements and modeled individual differences. Thus, in some models, I included subject as a random effect: for models that include this effect, every subject is given its own intercept. The equation modeling the results then becomes $Ln(P/1-P) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + Subj_i$, where $Subj_i$ differs for subjects 0 through i.

Visual condition, interface, and side (the side of the expected path), were independent variables. Visual condition was coded as in Table 3.1 by the type of comparison made (e.g., texture differences or friction). Interface was either joystick or the WIP metaphor. Side bias, a participant's tendency to select one side or another, was unexpected prior to conducting the experiment, but found during analysis – In particular, participants preferentially selected the path on the right hand side by a ratio of 29:23. To model this, we introduced a variable, side, that was coded "0" when the expected response was on the left and "1" when the expected response was on the right.

Other participant data: age, sex, gaming/non-gaming status, visual-kinesthetic scores, and subjective ratings were collected and treated as covariates in our analysis. Participants were deemed gaming if they recently and regularly played 3D perspective games and non-gaming if they did not (Table 3.3 for details.) The visual-kinesthetic score was tallied from a subset of questions from the multiple intelligences questionnaire (Table 3.2.) Answers of **Strongly Agree** were scored 5 points, **Strongly Disagree** were scored 1 point. Questions are either Visual or Kinesthetic in category, resulting in a Visual subscore and a kinesthetic subscore. The visual-kinesthetic score was then coded as a difference between the two subscores: $Difference = Score_V - Score_K$ where V refers to the visual subscore and K refers to the kinesthetic subscore.

The remaining data collected included: time from simulation start to goal, the number of times the participant stepped off the walking area, the number of times the trial had to be reset, and subjective ratings for the two interfaces (Table 3.4). These data were analyzed separately.

4.1 Model Fits

Starting from a full model, F-tests quickly ruled out age ($F[1, 818] < 0.001, p = 0.99$) and gender ($F[1, 818] = 0.049, p = 0.826$) as significant covariates. There was also no significant influence from covariates such as gaming/non-gaming status ($F[1, 818] = 0.047, p = 0.828$), or visual-kinesthetic scores ($F[1, 818] = 0.424, p = 0.515$), and subjective ratings ($F[1, 818] < 0.5, p = 0.387$). The log likelihood did not significantly improve with the inclusion of the covariates (-538.72 for final compared to -536.16 for the model including the dropped covariates.) Furthermore information criterion scores favored the final model over the covariate-included model, (AIC_{final}=1091.4 and BIC_{final}=1124.5, compared to AIC_{cov}=1102.3 and BIC_{cov}=1173.2) In addition, the final model explains a greater proportion of the variance between models and the data as compared to the covariate-included model (adjusted R^2_{adj}=0.0968, compared to the full model R^2_{adj}=0.095.)

With the covariates eliminated, we were left with a model that included visual condition ($F[3,818] = 17.53, p < 0.001$), interface ($F[1,818] = 6.17, p = 0.01$) and side bias ($F[1,818] = 12.17, p < 0.001$) as fixed effects, and the subject random effect (SD = 0.274, 95% CI of [0.123, 0.606]).

The addition of two-way interactions between the factors did not significantly improve the fit of the model based on comparisons of the Akaike and Bayesian information criteria (AIC and BIC). Candidate models that included one of the following two-way interactions were assessed relative to the base model: interface and visual condition (coded IV), interface and side (IS), side and visual condition (SV). Of these candidate models, AIC scores were higher for IV and SV ($AIC_{IV} = 1092.8$ and $AIC_{SV} = 1096.5$, compared to $AIC_{base} = 1091.4$) but not IS ($AIC_{IS} = 1090.4$). However, the base model scored better on BIC across the board ($BIC_{IV} = 1140.1$, $BIC_{IS} = 1128.2$, $BIC_{SV} = 1143.8$ compared to $BIC_{base} = 1124.5$). Given that these models with interactions were not significant improvements over the base model ($\Delta df_{IV} = 3, p_{IV} = 0.2$, $\Delta df_{IS} = 1, p_{IS} = 0.08$, $\Delta df_{SV} = 3, p_{SV} = 0.82$), the base non-interaction model (visual condition, interface, side bias fixed effects, and subject random effect) was selected as the final model on the basis of parsimony. The equation for the final prediction model is: $Ln(Expected/1 - Expected) = \beta_0 + \beta_1 Interface + \beta_2 Visual + \beta_3 Side + Subj_i$, where β_0 is the intercept term, β_1, β_2, β_3 are weights of the fixed effects, and $Subj_i$ is the subjects random effect.

4.2 Main effects

In hindsight, the walking-in-place condition was limited in its capacity to simulate realistic walking primarily in the turning agility afforded to users. It was relatively easy for those who wished to turn 180 degrees without displacing themselves using the joystick, but the same maneuver was nearly impossible to accomplish walking-in-place. This difference in maneuverability may have affected the decisions of some participants. Efforts were made to reduce the amount of steering participants needed to do on any given path, indeed, the planks were set apart at a 45 degree angle. Nonetheless, participants did not always take the shortest path, sometimes zigzagging on the walkways, and therefore occasionally found the need to adjust their heading. Thus the similarity of the implementation to real world walking may have thrown off participants when they encountered unexpected difficulty turning in place. In addition, our implementation of walking-in-place used head-directed motion, which is known to be suboptimal for producing realistic locomotion, as shown in the detailed analysis by Templeman, Denbrook, and Sibert (1999). This implementation was chosen because of current limitations in available tracking resources. In the future, we may be able to mitigate such an effect with more effective design of the walking interface.

My main hypothesis was that the naturalness of the interface would have a significant effect on the path choice. Consistent with this, the analysis in the previous section indicated that interface had a significant role ($p=0.013$) in determining participants' choice path. Figure 4.1 shows the average results per participant fitted to model predictions. The separation between Joystick and WIP conditions indicates that there are differences between the interfaces. WIP data points, being more densely clustered towards the upper right hand quadrant, seems to suggest that the WIP interface condition elicits slightly more natural behaviour. Overall, participants were somewhat more likely to select the more natural response when they used the walking-in-place metaphor as compared to when they used the joystick (on average 0.486 of the time using joystick, 0.567 of the time using walking-in-place metaphor).

Participant-to-participant, the proportion of expected responses ranged more widely with the joystick interface than with walking-in-place (maximum 0.81 and

0.75, minimum 0.25 and 0.31 for joystick and walking-in-place, respectively) with the median proportion of expected responses being somewhat higher with the walking-in-place condition at 0.56 compared to 0.44 for the joystick (See Figure 4.2).

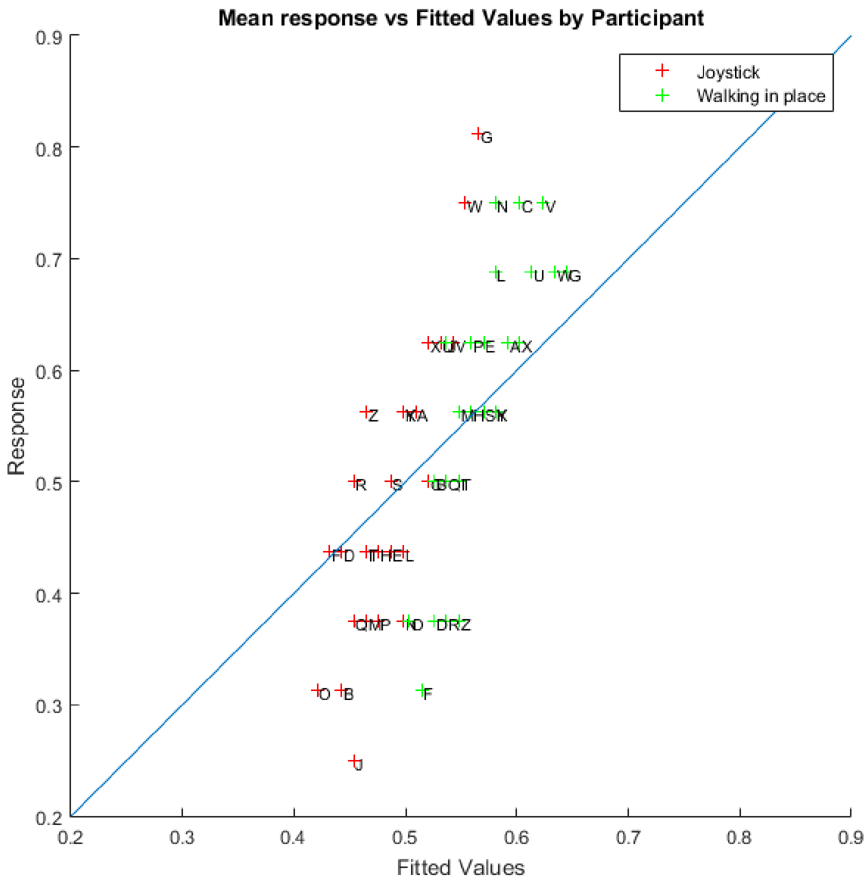

Figure 4.1: *Mean responses vs. fits by participant: proportion of correct responses fitted to model predictions, data for both interfaces, 26 participants, labelled A-Z.*

4.3 Differences in visual conditions

According to the model, visual condition played a highly significant role in participants' choices (see Figure 4.3). To visualize how the type of visual condition mattered in selecting the expected response, we averaged the participant's responses. We then conducted four separate paired t-tests (one per visual condition type) comparing joystick and walking-in-place metaphor results. The significance levels reported here are Holm-Bonferroni corrected.

Based on this analysis, when width conditions (t(25) = -3.503, p = 0.007) were presented, using the walking in-place condition (M = 0.763, SD = 0.158) was more likely to result in participants taking the ecologically expected path compared to

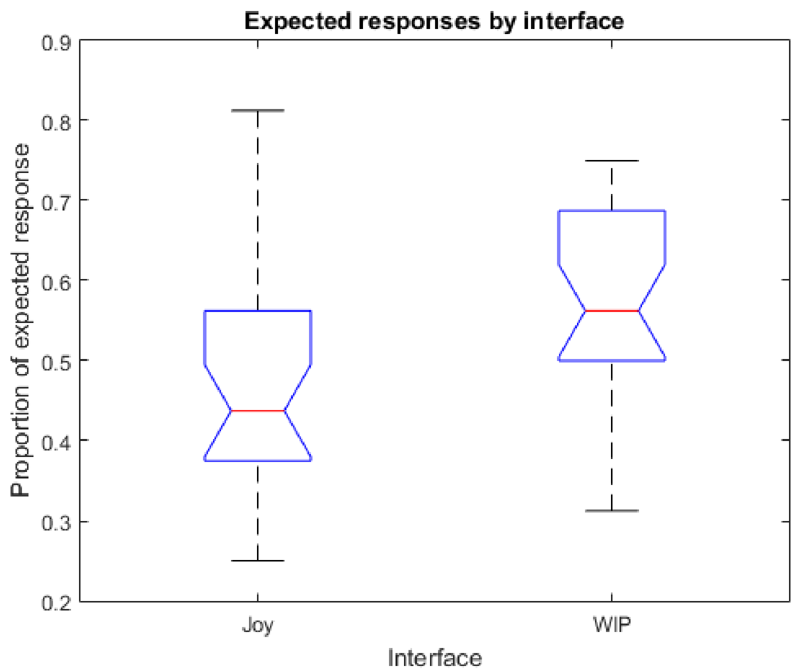

Figure 4.2: *Effect of interface on path choice. Proportion of responses per participant indicating the expected ecologically preferred choice, grouped by interface. Red line represents the median, box is the upper and lower quartiles and the whiskers are the range.*

joystick (M = 0.603, SD = 0.2). However, participants, during the path width condition, were at greater risk of actually navigating off platforms, whereas for the other visual path conditions, there were no real or virtual consequences to selecting the unexpected path. The likelihood of falling or running out of time across the other conditions did not differ depending on choice. The presentation of the other visual conditions conveyed admittedly hollow threats, and were only deterrents because of previous experience walking in the real world. None of the conditions impeded their progress across the paths enough to significantly alter the amount of time it took for them to make it to the goals, either. All else being equal, width conditions were the

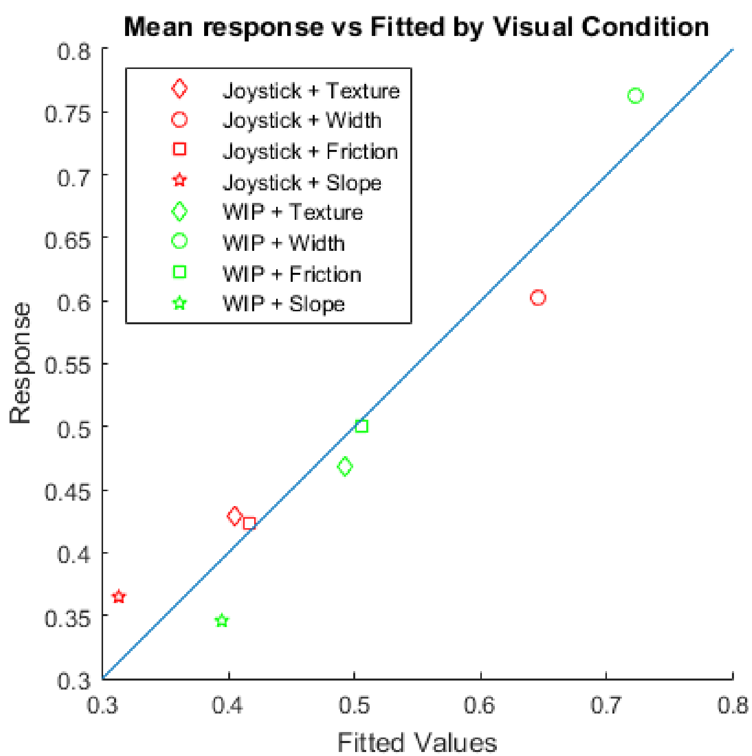

Figure 4.3: *Mean results vs. fits by trial: proportion of correct responses fitted to model predictions, symbols indicate all data organized by visual condition*

only conditions that presented actual challenges to participants in the VE.

For texture and friction visual conditions, there were no significant differences between walking-in-place (texture: M = 0.468, SD = 216; friction: M = 0.5, SD = 0.4) and joystick (texture: M = 0.426, SD = 0.212; friction: M = 0.423, SD = 0.366), conditions (texture: $t(25) = 0.782$, $p = 1$, friction: $t(25) = -0.778$, $p = -0.887$.) It is possible that the quality of the textures and the visual accuracy of the presentations may lessen the effect that interface has on choice of path.

Furthermore, some participants, upon seeing a new visual condition, informed the experimenter that they were deliberately choosing the more difficult paths. In fact, these participants remarked that they enjoyed walking on the upward slope because of the relative freedom from real life constraints that the virtual environment afforded them. Without the consequence of increased effort required to traverse the path, they enjoyed the novelty of effortlessly walking uphill, especially in the walking-in-place condition because of its similarity to real world locomotion but without the consequences. This may account for the lack of significant difference between the proportion of unexpected results for the walking-in-place (M = 0.346, SD = 0.419) compared to joystick (M = 0.365, SD = 0.414) during slope condition presentations ($t(25) = 0.328$, $p = 0.746$.)

The results here indicate that experiments using this paradigm should take care to impose suitable (in terms of experimental goals) in-environment penalties (such as sliding on a low friction path or slowing on a destabilizing surface) in order to provide some balance between the risks implied by the visual conditions and their impact in the VE.

In addition, as discussed previously, I made the assumption that humans were similar to animals in that they would make wayfinding decisions that were rational in so far as they presented visual conditions which minimized energy expenditure.

Based on the results seen during the slope condition, where users prioritized having fun over what made sense biologically, this assumption needs reevaluating. Also of note, user engagement has been demonstrated to be an important component of presence (Nacke and Lindley, 2008; Slater, Usoh, and Steed, 1995). The fact that participants reported enjoying the upward slope, contrary to expectations, means that we might have to consider a compromise between naturalness, and enjoyable or engaging situations.

4.4 Side bias

After analysis we discovered that a participant was more likely to select the natural choice if the path was on their favoured side. Participants in our experiment preferred taking the right path during the joystick condition 58.65% (±6.5%) of the time, and the right path during walking-in-place 52.88% (±4.9%) of the time. According to a paper by Scharine and McBeath (2002), given a choice of two paths, people are more likely to take right paths if they are right handed and if they drive on the right side of the road. Based on this finding, future studies using the two-choice path set up should record participant's handedness data and account for local traffic customs, or at minimum, be expected to adequately deal with a bias after gathering data.

4.5 Other observations

Additional data were collected, but not used in the models. In terms of the two interfaces, there was no significant difference in the time to complete the trial (average time 13.6 ± 8.1 seconds for joystick, 13.7 ± 9.8 seconds for WIP). Between all condition combinations (visual and interface), repeated measures ANOVA indicated that there

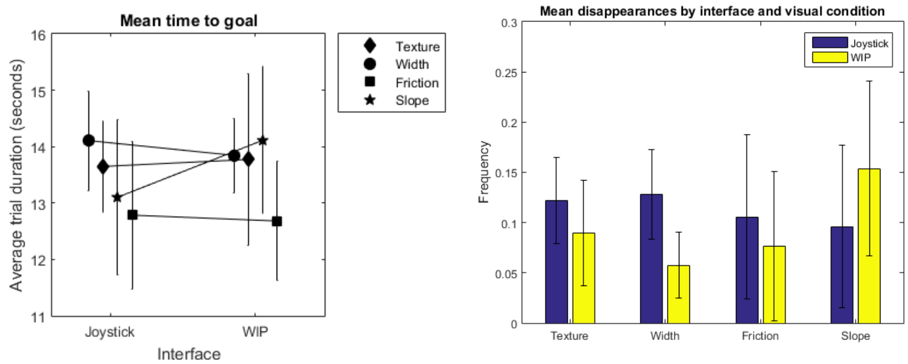

Figure 4.4: *Left: Mean time taken to traverse paths per trial, separated by interface and visual condition. Right: Mean frequency of plank disappearances per trial, separated by interface and visual condition*

were no significant effects of interface or visual condition in the time to complete the trials. See Figure 4.4.)

As described above in the Methods section, planks randomly disappeared to encourage the users to make their choices and walk to the goals as quickly as possible. No significant difference in the frequency of plank disappearances was found between the two interfaces (6% of the time for joystick, 4.2% of the time for WIP). Repeated measures ANOVA analysis did not reveal any significant effects of interface or visual condition in the frequency of plank disappearances (Figure 4.4).

However, the number of times that the user fell off the walkways (7% of the time for joystick, 10.8% of the time for WIP) differed significantly between interfaces. Repeated measures ANOVA analysis determined that in the case of falls, interface had a significant effect at $F(1,25) = 10.07$, $p = 0.004$. Pairwise t-tests between the combined conditions indicate that falls differed between the interfaces when slope was presented, $t(25) = -3.07$, $p = 0.005$ (Holm-Bonferroni corrected).

A higher average number of falls in general likely indicates differences specific to the locomotion techniques themselves: joystick flying allows a person to stop with much greater precision, but our WIP technique is step-based; once users lift a foot, they cannot stop on a dime and must eventually place the swing leg back into stance. If it happens that a user finds themselves in single support, but at the edge of a plank, placing their swing foot back into double support would move them forward, moving them past the edge. Our WIP implementation also allowed users to move at speeds much faster than the maximum speed of the joystick, which would have made users more prone to falling if they were stepping quickly enough. We noted previously in section 4.3 that users tended to choose the opposite of expectations when slope conditions were tested. The unexpected results for WIP and the falls might indicate more risk-taking behaviour in that condition. In this case, future studies using a slope condition may consider administering a risk-taking inventory and treating those results as a covariate.

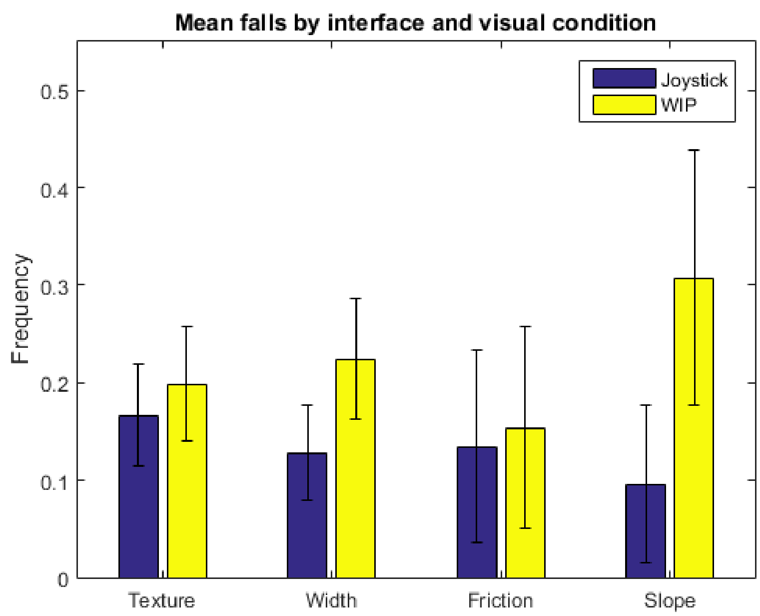

Figure 4.5: *Mean falls taken per trial, by condition.*

Participants were asked specifically about their perceived body size after early participants spontaneously reported body size perception discrepancies. They reported that they tended to feel as if they were shorter in the joystick condition as compared to WIP, often pointing their noses into the ground when walking in the joystick condition. Four participants reported this phenomenon after we started recording these incidents. Also, as individual gaits and walking speeds vary, some participants noted that their expectations of the avatar's visual displacement did not match their own eye height. Somewhat paradoxically, some reported that the naturalness of the WIP interface condition only served to heighten the disparity between the height of the view and the step length of the avatar and their own heights and their average step size.

Another phenomenon we began recording after the early stages of the experiment was interface effect on nausea. Six users who experienced motion sickness noted that WIP made them less nauseous than the joystick condition, though attempts were made to minimize motion sickness in both interfaces. This was most probably due to consistent visual and vestibular inputs from the the body moving back and forth during walking-in-place, which reduced some of the discomfort stemming from the sensory discrepancies between vision and vestibular information despite the lack of true forward vestibular motion (Hettinger, 2002). When asked, all of the participants who felt ill reported that the discomfort was very mild and opted to complete the entire experiment, despite knowing that they were free to stop at any time.

As seen above, there was no significance between participants with different Visual/Kinesthetic scores. This result was not entirely unforeseen as the work of Witmer and Singer (1998) had already demonstrated that intelligence types were not significant in user performance. Conversely, the counterintuitive experiment results in the slope condition demonstrated that differences in risk-taking behaviour may greatly effect people's choices. In general, the selection of questionnaires and inventories as an addition to this paradigm should be refined.

As said previously, a bias towards selecting the rightmost path was found during the statistical analysis. Future studies using the two-choice path set up should record participant's handedness data, or at minimum, be expected to adequately deal with a bias after gathering data.

During the course of the experiment, technical issues prevented the proper functioning of 3D images in the display. Because the purpose of the study was to look at the effect of different visual conditions under different interfaces, the usage of stereo over non-stereo images was not considered critical. In hindsight, because 3-dimensional information is used to judgments about surface properties, the friction and texture conditions may have been affected. 3D stereoscopic versus monocular view may change responses, especially where surface texture and friction are concerned.

Chapter 5

Conclusion

In this thesis, I presented a method of obtaining a comparative measure of a locomotion interface's efficacy in inducing presence. The strength of this method lies in the simplicity of obtaining and analyzing the data across two or potentially more interfaces. By treating naturalness of interaction as a behavioural correlate for presence, the method also aims to be more objective than traditional interface quality assessment methods such as questionnaires.

The results of the study provide evidence that different locomotion interfaces elicit different user behaviours, thus reinforcing the importance of considering senses that work in addition to, and in conjunction with visual stimuli when designing locomotion interfaces. The most straightforward engineering or industry application will be a tool for benchmarking locomotion interface designs. The results also unequivocally demonstrate that locomotion interfaces have far to go in terms of their naturalness and realism, thereby emphasizing the importance of developing naturalistic locomotion interfaces.

Though the more immediate aim was to produce a " test," this framework may have applications in more theoretical uses: the findings may be useful in applications not only in engineering and psychology, but can be used to inform methodologies or practices in other fields. As said before, the appeal of studies utilizing virtual reality lies in the investigator's ability to better manipulate the environment than in real world laboratories (Loomis, Blascovich, and Beall, 1999). Such a test could indicate a greater degree of confidence in the ecological validity of experiments done using certain interfaces over others. The paradigm introduced in this paper can be used in conjunction with real world testing in order to evaluate experimental methodologies and equipment configurations in behavioural studies.

The relative strengths and weaknesses of different interfaces can be used to select appropriate locomotion controllers for virtual reality studies in behavioural, biological and medical sciences. Architects or civil engineers aiming to implement virtual tours or simulations of their design space, especially where traffic flow is of concern, may also see value in this work as well.

5.1 Future work

It is important to note that the visual path conditions are by no means complete – there is a large variety of conditions that can be considered. These conditions were chosen on the basis of their simplicity to implement and straightforward predictions of natural behaviour and are thus not comprehensive; a simple way to extend this study is to add a greater number of either visual or interface conditions. Originally, treadmills were considered, but given the pilot nature of the study, it was deemed similar enough to the walking-in-place metaphor. That being said, it is possible that future studies may use a treadmill as an additional condition to further study the effects of different interfaces. Treadmills, have more proprioceptive similarity to real world walking than stepping, especially omnidirectional treadmills, and could see even more natural behaviour compared to my WIP implementation.

Visual conditions such as curving paths or obstructed paths could produce interesting behaviours. Additionally, visual conditions could be combined and then compared. For example: combine walking on a slope with low friction conditions, an especially hazardous condition. It may be that using some devices will cause participants to prioritize some visual conditions over others when multiple conditions exist. For example, participants may be more likely to choose a narrower pathway if the alternative is to walk on a low friction surface which is also inclined downward because the combination of factors pose a greater risk of slip and fall than the likelihood of loss of balance. This possibility is likely to be of use to those interested in the higher level cognitive aspects of wayfinding and navigation.

Though promising results were seen in this experiment, the validity of this paradigm could be tested by doing a similar experiment using a real life environment, though given characteristics of the virtual environment, we would have to concede some similarities in favour of participant safety. Another way of testing the validity of this paradigm is to use the questionnaires of Usoh et al. (2000) or Witmer and Singer (1998) to see if we can produce consistent results between the questionnaires and our findings.

Yet another way of expanding this paradigm is to take bio-mechanical measures in addition to recording whether or not participants select the expected path. Though users may not choose the ideal path, they may alter their gait or posture under different conditions. This would not be difficult to achieve with the proper motion tracking system setup. On the same note, as users reported perceived size discrepancy between the interfaces and between their own perceived size and gait speed and length, it stands to reason that individual differences may weigh in on the subjective realism inside a VE. In addition, given that perception of one's own body will determine behaviours such as ducking under low ceilings or turning to the side in narrow passages in real life, there may be potential in modifying this paradigm to use body schema instead of visual wayfinding when evaluating interface quality.

Another way to compare the impact of visual and interface conditions is to trace the path of the participant's walk. The work of Grant and Magee (1998) suggest that the directness of the line from origin to goal can be considered an aspect of success. It may also be an additional indicator of a participant's confidence in their choice.

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